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Progress and methodologies of lifecycle commissioning of HVAC systems to enhance building sustainability

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A B S T R A C T

Building energy consumption keeps rising in recent years due to growth in population, increasing demand for healthy, comfort and productive indoor environment, global climate changing, etc. Nowadays, the contribution from buildings toward global energy consumption is approximately 40%. Most of energy use in buildings is for the provision of heating, ventilation and air conditioning (HVAC). High-level performance of HVAC systems in building lifecycle is critical to building sustainability.

As a quality-oriented process, commissioning has been recognized as a valid means to improve performance of buildings and HVAC systems in both energy and environment aspects and should be conducted regularly or continuously throughout the whole building lifecycle. At the same time, building automation systems (BAS) are now standard in most modern buildings. Besides automatic monitoring and control of building services systems, automatic commissioning is a new expectation on modern BAS to save labor, time and cost required by manual commissioning and improve the effectiveness of commissioning. This paper firstly takes a brief look at current situation of building commissioning in research and application world wide, and then summarizes state-of-the-art techniques for automatic commissioning of HVAC systems. It is concluded that, to maximize benefits from commissioning for enhancing building sustainability, more efforts should be made to develop automatic commissioning tools which can be integrated with modern BAS.

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Contents

1. Introduction

Buildings consume energy in their whole lifecycles from planning, design, construction and installation to operation and maintenance. Building energy consumption keeps rising in recent years due to growth in population, increasing demand for healthy,

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comfort and productive indoor environment as well as global climate changing. Nowadays, the contribution from buildings toward global energy consumption is approximately 40% [1]. Building energy-efficiency and sustainability continues to be one of the major concerns in a sustainable society. Most of energy use in buildings is for the provision of heating, ventilation and air conditioning (HVAC), which takes about 50% of building energy consumption on an average [2]. High-level performance of HVAC systems in the whole building lifecycle is critical to building sustainability. Professionals in the building industry have been well aware of it and made great efforts to improve lifecycle performance of HVAC systems, such as setting up high expectation and design criteria from the very beginning, selecting energy-efficient materials and equipment and implementing optimal control strategies. Djuric and Novakovic accounted for the necessities of building commissioning from three aspects including faults in building operation, legislative force and commissioning benefits [3]. Usually, HVAC systems rarely performs as well in practice as anticipated in design due to incomplete documentation for verification, insufficient information exchange among different roles (such as architects, consultants, suppliers, contractors and operators), improper equipment selection and installation, lacking of proper and prompt maintenance, poor feedback on operation performance, performance degradation and even complete failure of components, etc. Commissioning is a valid means to ensure HVAC systems perform in building conformity with design intent, hence enhance building sustainability.

Commissioning has traditionally been viewed as a task performed after system assembly and before hand-over as a final checkout and acceptance test. The definition of commissioning is evolving fast these years. According to ASHRAE Guideline 1–1996 [4], commissioning is the process of ensuring that systems are designed, installed, functionally tested and capable of being operated and maintained to perform in conformity with the design intent. Therefore, commissioning is a process rather than a one-off task, which should be carried out regularly or continuously throughout the whole building lifecycle from early planning, design, construction and installation to occupancy and operation. This philosophy has been widely accepted in North America and Europe. In US, National Conference on Building Commissioning (NCBC) has been held once a year since 1992. Commissioning has been recognized as a valid means to improve energy performance of buildings and HVAC systems by International Energy Agency (IEA) [5,6] and should be performed throughout the building lifecycle. Many international organizations have been put significant efforts into research and development in lifecycle commissioning of HVAC systems, such as IEA, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Lawrence Berkeley National Laboratory (LBNL), Air-Conditioning and Refrigeration Technology Institute (ARTI), Charted Institution of Building Services Engineering (CIBSE), French National Center for Building Science and Technology (CSTB) and National Institute of Standards and Technology (NIST), Portland Energy Conservation, Inc. (PECI) and Pacific Northwest National Laboratory (PNNL). Their contributions in the area of building commissioning are available in their official websites. Some typical and influential work will be summarized in the following parts.

This paper firstly introduces current situation of commissioning in both research and application. In doing this, the future of building lifecycle commissioning as an industry is foreseen. Then, this paper introduces state-of-the-art techniques for implementing automatic commissioning of HVAC systems. Considering intensive labor, time and cost demanded by manual commissioning, automatic commissioning is preferred. The widely used BAS provide useful platforms for performing lifecycle commissioning of HVAC systems.

2. Overview of building commissioning

2.1. Development of building commissioning

Commissioning is not a recent development. Table 1 provides an illustrative timeline of the development of building commissioning [7]. Both the scope of commissioning and techniques used in commissioning expand rapidly these years. First, building commissioning is widely recognized as a systematic lifecycle process rather than a one-off task. Secondly, with the increasing demand for indoor environment quality as well as the increasing complexity of modern buildings and their associated services systems, the scope of work of commissioning is expanding largely. Therefore, more cost-effective means of commissioning is expected. Thirdly, commissioning techniques are improved with the technology progress. Building commissioning has been evolving in three major phases, i.e. manual testing, adjusting and balancing (TAB) after installation and before operation, manual periodical commissioning in building lifecycles and automatic commissioning. The new phase hardly takes the place of the old ones due to the constraints of present technology level as well as irreplaceable manual checking and testing in a commissioning process. The manual commissioning is dominating the building commissioning industry.

Commissioning of HVAC system is always one of the main tasks of building commissioning. Traditionally, the term "commissioning" has often referred to the one-off task by which the HVAC system of a building was manually tested and balanced (TAB) according to established standards prior to acceptance by the building owner. Many professionals in the HVAC field has recognized the great benefits from lifecycle commissioning of HVAC systems, including energy-saving implementation from the earlier planning phase, effective management of mass data, lower energy consumption, timely rectification of abnormalities of components, safer and healthier indoor environment, long-term tenant satisfaction, prolonged life of equipment, etc. However, few professionals including consultants, developers, contractors and field engineers see these benefits, on the contrary, most of them think lifecycle commissioning demands huge labor and time and with uncertain benefits. Therefore, in the R&D area of building commissioning, many efforts have been put on the cost effectiveness analysis of commissioning as well as promoting independent third party agents or professional authorities who are responsible and qualified for building commissioning in market recently. One of LBNL projects [8] found a media payback period of 4.8 years for commissioning of new buildings in United States. It also concludes median cost saving on energy of 15% and payback periods of 0.7 year for periodical commissioning of existing building. Besides demonstrating the benefits to lure the interests from the industry, many international organizations devote to promote the lifecycle commissioning. For example, building commissioning has been

Table 1
Development of building commissioning

1950	Building commissioning introduction in Europe
1960	Growth of environmental consciousness
1970	TAB introduction in North America Energy crisis
1980	Building commissioning introduction in North America
1990	US Energy Policy Act of 1992 ASHRAE Guideline 1-1996... CIBSE Commissioning codes
2000-	TAB of automatic controls and building commissioning growth all over the world

made a prerequisite for Leadership in Energy and Environment Design (LEED) certification [9]. This in turn has greatly increased the awareness of building commissioning among architects and building owners alike. To earn additional credit toward the total points needed to achieve LEED certification, more comprehensive commissioning is preferable.

At the same time, the growing scales and complexities of modern buildings result in that manual commissioning faces great challenges in view of man-power, constraint of project schedule, cost as well as reliability. Therefore, R&D of automatic commissioning is increasingly active in these years. Before the wide application of automatic control and BAS in buildings, it is infeasible for performing commissioning automatically. Although commissioning of HVAC systems nowadays is far away from totally automated, some experts believed that the technology progresses, including wireless communication, automated diagnostics, advanced control, etc., will lead commissioning to the state where building systems and equipment is automatically commissioned on an on-going basis in 20 or 30 years [10].

2.2. Categories of building commissioning

As commissioning should be performed throughout the building lifecycle, commissioning involves in every phases in a construction process. To distinguish different types of commissioning helps to specify commissioning objects, actions, procedures and outcomes. Generally, there are four types of commissioning, i.e. initial commissioning, retro-commissioning, re-commissioning and on-going or continuous commissioning [4,5]. They may appear in different terms, but these four types are representative and widely accepted.

- **Initial commissioning** is a type of commissioning applied to a production of a *new* building and/or an installation of *new* systems, which is defined as a systematic process beginning with Program Step and ending with Post-Acceptance Step.
- **Retro-commissioning** is the first time commissioning implemented in an *existing* building in which a documented commissioning was not implemented before.
- **Re-commissioning** is a commissioning implemented after the initial commissioning or the retro-commissioning when the owner hopes to verify, improve and document the performance of building systems.
- **On-going/continuous commissioning**® is a commissioning conducted continually for the purposes of maintaining, improving and optimizing the performance of building systems after the initial commissioning or the retro-commissioning.

The difference between initial commissioning and retro-commissioning is the commissioning objects. The former aims at new buildings and new installations; however, the latter aims at existing buildings and installation. In many cases, design documents and system manual of the existing building have been lost or unmatched with the current situation. Therefore, the retro-commissioning would include verification process on the design as in parts of the initial commissioning.

Re-commission is required because of a modification in the user requirements, the discovery of underperformance of the systems, the wish to fix faults found during the initial commissioning, etc. Periodic re-commissioning ensures that the original performance persists. The re-commissioning is the event that re-implements the original commissioning in order to keep the building systems performance. Both the re-commissioning and the on-going commissioning are performed after the initial commissioning or the retro-commissioning, but they are different in their objectives and means to implement them. The large difference between on-going commissioning and periodic re-commissioning is that the re-commissioning refers to the original building systems performance, but the on-going commissioning lays emphasis on the performance optimization. The on-going commissioning is a successive commissioning process during Operation & Maintenance (O&M) phase to resolve operational problems, improve comfort, optimize energy use, and recommend retrofits if necessary.

In a sum, HVAC system commissioning is a process involving in various components by various activities (such as documenting, testing, monitoring, fault diagnosis, training), which is performed throughout the whole building lifecycle for enhancing building sustainability.

2.3. Manual commissioning guidelines of building systems

Commissioning of a modern building is a huge project. As discussed above, manual commissioning is dominating the building commissioning industry. Thousands and hundreds of components, such as sensors, valves, dampers, lights, coils, pumps, and chillers, and various services systems, such as HVAC system, electrical system, fire system and plumbing system need to be documented, tested, balanced and repaired or replaced. To ensure that building systems are manually commissioned in a proper and timely manner, clear and systematic step-by-step guidance and regulations are necessary. Many manual commissioning guidelines, codes or standards have been issued by different organizations and in different countries. Some representative guidelines are shown as follows:

- ASHRAE Guideline 1-1996: The HVAC Commissioning Process.
- ASHRAE Guideline 0-2005: The Commissioning Process.
- BSRIA AG01/91: Commissioning of VAV systems in buildings.
- CIBSE Commissioning Code A: Air balancing (1996).
- CIBSE Commissioning Code L: Lighting (2003).

From these guidelines, it can be found that manual building commissioning is a labor-intensive and time-consuming work. It is impossible that building commissioning is performed periodically or continuously in the whole building lifecycle. Automatic building commissioning is a way out.

3. Automatic commissioning of HVAC systems

It has been analyzed that automatic commissioning of HVAC systems is necessary due to the increasing demands on building sustainability and growing complexity of modern buildings. At the same time, automatic commissioning of HVAC systems is also feasible with the development of technology. Major work scope of commissioning includes documenting all kinds of activities, functional performance testing, O&M staff training as well as performance monitoring and FDD during operation. It is impossible using single technique to automate all tasks, especially when different tasks target different components, which have different characteristics, such as chillers, pumps, cooling towers, air-handling units and various terminals. It is always the truth that every shoe fits not every foot. Therefore, different automation techniques are deployed by identifying characteristics of different work which are suitable for automating. Current automatic commissioning work can generally be grouped into three tasks, i.e. automatic information management, automatic functional testing and automatic performance monitoring and fault diagnostics. No complete automatic commissioning tool, which can accomplish all these tasks, has been reported openly. However,

automatic commissioning tools, which can accomplish part of the tasks, do widely exist.

3.1. Computer-based information management

Normally, the information used in commissioning is found within numerous documents including various reports, memos, specifications, submittals, drawings, manuals, etc., and the information is usually saved in different formats (Word, Excel, and even hardcopy with handwriting) and by different personnel such as developers, architects, consultants, contractors and suppliers in different phases. Since HVAC systems are tested, maintained and retrofitted from time to time throughout building lifecycle, the information useful for commissioning might be updated and enriched. Therefore, the information management should track and record the all changes of HVAC systems in the building lifecycle. The accuracy, conformity and consistence of said information are vital because it not only influence the time and labor consumed in commissioning, but also determine the effectiveness and efficiency of commissioning to a large extent. With the development of computer technology, there have been more and more interests in computer-based automatic information management because it is more efficient and reliable than the conventional way using hardcopy in HVAC system commissioning processes. R&D efforts of ASHRAE, LBNL and PECI present the state-of-the-art techniques of automatic information management for commissioning HVAC systems.

As early as 1996, LBNL initiated a research project on developing Building Life-cycle Information Systems [11] and presented a prototype chiller commissioning tool to assist in the construction, execution and archiving of commissioning plan. This research project set up a basic framework for the computer-based information management, and most of the following R&D in this field is based on it. Design intent tool, jointly developed by LBNL and PECI [12] for the California Institute for Energy Efficiency, mainly aims at recoding design intent in the design process and provides a structure approach to recording design decisions that impact a facility's performance in areas such as energy efficiency. Using the tool, owners and designers alike can plan, monitor, and verify that a facility's design intent is being met during each stage of the design process. Additionally, the tool gives commissioning agents, facility operators and future owners and renovators an understanding of how the building and its subsystems are intended to operate, and thus track and benchmark performance. A data model was developed in ASHRAE TRP-1032 [13,14] for managing the data in two HVAC subsystems, i.e. the chilled water system and a variable-air-volume (VAV) air distribution system, after identifying 250 data necessary for commissioning and operation. An important concept was insisted on in the development of the data model, i.e. *interoperability*. Interoperability demands that the desired information is uniquely identified so that various software applications (such as automatic functional testing, monitoring and diagnostics, which will be explained in the following parts) can search for and extract the information from the data collection. To implement interoperability, the data model was developed to follow industry foundation classes (IFC) set up by International Alliance for Interoperability (IAI) [15]. The IFC model defines a universal, virtual representation of every aspect of the design, construction, and operation of elements found within buildings and is a formalization of data structures that are necessary for the meaningful exchange of information between different software applications. For example, the nominal chiller capacity in the design phase is stored in the *Chiller* object's *FullLoadCapacity* attribute as defined in the *Chilled Water System* schema. This attribute points to a data type of *MeasureWithUnit*, which is in the resources schema and consist of a *ValueComponent*, *Name*, and *UnitComponent* attribute.

In summary, automatic information management is pre-requisite for automatic commissioning of building systems. Interoperability between information management tools and other commissioning tools is critical. R&D on this aspect is fruitful and provides template and rules for customizing automatic information management tools or database in practice.

3.2. Automatic functional performance testing

Functional performance testing is traditionally an important part of T&C, but is usually performed in the initial-commissioning process as far as building lifecycle commissioning concerned. It includes tests demonstrating that the equipment/installation will meet the intended performance specified in the design documentation. Functional testing covers tests of individual components including chillers, cooling towers, air-handle unit (AHU), fans, pumps, control systems and BAS, and tests of the system that distribute the HVAC systems throughout the buildings, such as water and air distribution loops. Functional testing should encompass all seasons under all kinds of normal operating conditions, such as full load and part load conditions, because most HVAC systems operate year-round. However, it is very difficult to meet such demands due to constrain of occupancy and testing schedule. Therefore, functional testing is usually performed by creating false operating conditions or through manipulating setpoints. By observing system reaction and comparing with design intent, performance degradation can be found and rectified. Regularly scheduled manual functional testing is expensive and time-consuming. BAS provide an efficient and economical platform for automatic functional testing because most control parameters, including sequence schedules, setpoints, control signals as well as proportional gains, integral and derivative times in widely adopted PID controllers, can be changed in it.

Automatic functional testing and automatic lifecycle functional testing in particular is relatively newer compared with automatic information management as above-mentioned and automatic performance monitoring and diagnostics to be discussed in the following section. In the research report provided by PECI in 2003 [16], it was mentioned that active functional testing had not been automated although it was entirely conceivable to be automated. Since functional performance testing is an essential part in building commissioning, the requirement on automating functional testing is growing with increasing demand on automatic continuous commissioning. A model-based method was present for performing automatic functional testing in air-handling units [17]. The method is based on an integrated lifecycle approach to HVAC commissioning and use component-level HVAC equipment models implemented in an equation-based simulation environment. Two kinds of testing approaches were used, i.e. open loop testing and close loop testing. Open loop testing checks whether the mechanical system works properly over the full range of operation by overriding controllers and force the mechanical equipment to the desired operating points. Close loop testing checks the coupled behavior of the mechanical equipment and the controller and identifies problems relating to control sequences, tuning, etc. The method is capable of detecting abnormalities of mixing boxes, variable-air-volume fan systems and cooling coil subsystems, such as leakage of outside air damper, sensor offset/failure, and poor loop tuning. Another paper presented the development of reference models for use in automatic functional testing [18]. Reference models developed from first principles and empirical relationships are used to represent normal operation of air-handling units. The cooling coil can be tested using a step test,

in which the valve is moved from close to open in a signal step to demonstrate the proper direction of valve operation and full flow capacity. At the closed position, water leakage of the valve can be revealed.

Moreover, functional test results need to be recorded in the information management database. The actual system performance, which may be different from that specified in design phase due to practical problems, such as multiply pumps in parallel installation, will be used as benchmark in later performance monitoring and diagnostics.

3.3. Automatic performance monitoring and fault diagnostics

Due to abnormal physical changes or aging of HVAC components, poor quality and inadequate maintenance, HVAC components easily suffer from complete failure (hard fault) or partial failure (soft fault). Although the losses caused by faults are difficult to quantify, the potential savings out of faults and non-optimal operation of HVAC systems alone in commercial buildings were estimated to be 20–30% [19]. Faults may cause inappropriate reference or design value, physical damage of components, poor IEQ and energy waste. Performance monitoring and fault diagnostics aim at finding those faults and rectifying them automatically or by operators. Faults may come from different stages of a HVAC system lifecycle, from design, installation, test and commissioning to operation and maintains. Therefore, a lifecycle commissioning is necessary for reliable and optimal performance of HVAC systems. Before wide recognition of automatic commissioning, R&D on fault detection and diagnosis (FDD) has been active for more than two decades, from earlier investigation on methodology of automatic FDD, development of automatic tools to nowadays implementation and validation of these tools in practical application [20–22].

Automatic performance monitoring and FDD are one of the important technologies needed for automatic commissioning, and they play essential roles in on-going/continuous commissioning of HVAC systems. Performance monitoring can be considered as a kind of simple fault detection in that both of them aim at finding degradations and abnormalities. Performance monitoring is continuously done under natural operating conditions by limit checking on direct (readings taken from BAS, such as temperature, flow rate and pressure) and indirect performance indexes (calculated from readings, such as coefficient of performance, COP). The sensitivities of different measurements to each typical fault in chillers were identified for automatic performance monitoring and FDD [23]. Simple techniques, such as trend analysis [24], can be used for monitoring performance. LBNL sponsored a multi-year project to develop an Information Monitoring and Diagnostic System (IMBS) by applying continuous building performance measurement, supporting information processing and data visualization technologies [25–28]. Some two-dimension and three-dimension plots were used to diagnose problems in the performance of building energy systems and provide owners and managers with reliable, decision-oriented information. For example, the two-dimension plot of chiller load (tons) versus chiller efficiency (kW/ton) was used to diagnose degradation in efficiency of the chillers, and full load or part load performance and chiller over-sizing or under-sizing problems. IMBS is a performance monitoring tool with limited automatic FDD ability.

More complicated techniques are usually employed in FDD. Fig. 1 shows a typical FDD process to detect, isolate and evaluate fault in a real process. FDD methods can be roughly divided into two categories, i.e. model-based methods and model-free methods. The model-free methods do not utilize explicit mathematical model of the target system. For examples, the physical/simple redundancy method adopts several sensors to measure the same physical variable simultaneously [29]. Any serious discrepancy among the measurements indicates existence of sensor fault. Another model-free FDD method is spectrum/noise analysis of system measurements [30]. Most variables exhibit a typical frequency spectrum under normal condition, so any deviation is an indication of abnormality. The model-free methods are comparatively easier to be implemented because difficulties in building models are avoided. They are weak in dealing with large-scale and distributed systems, such as HVAC systems.

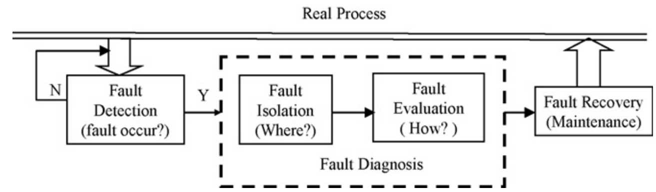

Fig. 1. Flow chart of a typical fault detection and diagnosis process.

The model-based FDD methods usually use reference models, which require either deep understanding about the investigated systems, or high mathematic technique and rich data to set up models or identify model parameters. By comparing discrepancy between outputs from real process and outputs from models, so-called residual in the FDD field, abnormality can be detected if an unreasonable discrepancy exists. The logic schematic of model-based FDD methods is shown in Fig. 2. Reference models can be grouped into three categories according to whether the models can be physically explained and understood, i.e. physical models (such as equations based on energy and mass conservation [31]), grey models or hybrid models [32] and black models (such as neural network [33] and the statistical model [34]). Model-based methods are powerful to deal with various faults in various processes owing to flexible model types available; however, model uncertainty and inaccuracy may greatly affect performances of the methods. Many automatic FDD tools have been developed based on the methods, such as the diagnostic tool integrated in BAS for online sensor healthy monitoring in air-conditioning system [35,36] and CITE-AHU which is an automated commissioning tool for air-handling unit [37]. For detailed R&D in the HVAC field, readers can refer to two review papers on automatic FDD methods [38,39]. Although there are many different ways to develop FDD strategies and tools, there is unlikely to be a "best" or "overall" solution to all faults of all components in HVAC systems. Commissioning needs to effectively combine different techniques.

Automatic functional testing is a kind similar to automatic FDD in that both of them aim at finding abnormalities in HVAC systems, and sometimes they share similar techniques [40]. The former is an active action, but the latter is a passive one. No matter what kind of mathematic approach or physical model is used, automatic FDD is always conducted based on data retrieved from BAS, and the FDD process seldom interferes with the HVAC process except for

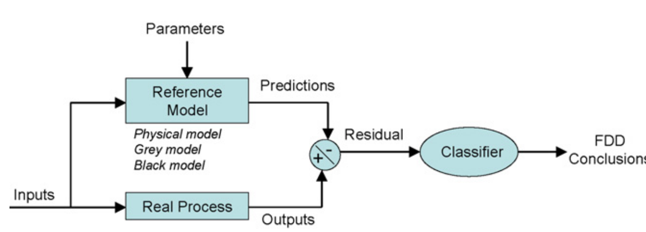

Fig. 2. Logic schematic of model-based FDD methods.

automatic recovery for achieving fault-tolerance. However, automatic functional testing is an active process because it is performed by changing process parameters or operation conditions. Automatic function testing is valuable not only for acceptance test in initial commissioning, but also for severe fault prevention or prognostic in building lifecycle. However, since functional testing may interfere with real process and affect the indoor environment, it ought to be performed cautiously and properly while the tested building is occupied.

4. Conclusion

As a valid means to improve building sustainability, building commissioning should be performed periodically or continuously in the whole building lifecycle. Due to intensive labor and time required by manual commissioning of modern buildings, lifecycle commissioning is infeasible currently. Automatic commissioning helps to save labor, time and cost of commissioning and is a way to more sustainable buildings.

HVAC systems consume most energy use in buildings and therefore they have attracted most attentions in building commissioning. Automatic lifecycle commissioning of HVAC systems is experiencing a rapid development through international cooperation in R&D on automatic building information management, automatic functional testing and automatic performance monitoring and diagnostics. With the development of technology, it can foresee a future when BAS-based automatic lifecycle commissioning of HVAC systems is widely implemented.

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